EXPERIMENTAL INVESTIGATION OF
VENTILATED CAVITIES

by

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Thesis Supervisor:
Professor Patrick Leehey

May 17, 1968

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ABSTRACT

Experimental Investigation of Ventilated Cavities

Richard James Kinnear

Submitted to the Department of Naval Architecture and
Marine Engineering on 17 May 1968 in partial fulfillment
of the requirements for the Master of Science degree in
Mechanical Engineering and the Professional Degree, ··
Naval Engineer.

A wedge with a 3.5 inch chord and a half-angle of
4.1 degrees is tested in the MIT Propeller Tunnel. No
pulsations were observed on the cavity. Thus, the
attempt to verify the theory that pulsations are possible
in an infinite medium (without a free surface) is in-
conclusive.

Although there exist a variance in the cavitation
number between theory and experiment, the data plotted
show that the general shape of the curve for a 4.1
degree wedge is correct. The primary discrepancy is
in the pressure recording methods.

Visual observations become difficult when ventilated
cavities are generated in the test section. It takes only
about 5 to 10 seconds for the air introduced into the
cavity to recirculate through the tunnel.

Thesis Supervisor: Patrick Leehey
Title: Professor of Naval Architecture

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The author would like to express his gratitude to his thesis supervisor, Professor Patrick Leehey, from whom his interest in this subject arose. Thanks are also extended to Robert K. Ashworth, Propeller Tunnel Technician, for his help in setting up the apparatus for the experiments.

LIST OF FIGURES

SYMBOLS

a_g	speed of sound of the gas contained in the cavity
k	reduced frequency of pulsation $= w\ell/U$
ℓ	cavity length
ℓ_o	cavity length/chord length
M^*	equivalent Mach number $= \left(\dfrac{\rho\, U_c^2}{\rho_g\, a_g^2}\right)^{1/2}$
P_c	cavity pressure
P_∞	ambient pressure
R	gas constant
T	temperature of the water
U_c	velocity along cavity
U_∞	uniform free stream velocity
α	chord length/breadth of channel
β	chord length/cavity length
γ	half-angle of wedge
ρ	density of the free stream
ρ_g	density of gas contained in the cavity
σ	cavitation number
ω	frequency of pulsation

I. INTRODUCTION

Cavity pulsations were first observed in 1961 by Silberman and Song (1)*. A two-dimensional, vertical, free jet water tunnel was used in their experiment. Definite pulsations of the cavity were observed at a critical cavitation number. One of the conclusions drawn by Silberman and Song was that a free surface was necessary for these pulsations to take place.

Then in 1962, Song (2) did some analytical work on pulsating cavities and compared his results with experiments. In general, good agreement was obtained. Again, Song concluded that a free surface was essential for pulsations of cavities.

Stimulated by these works, Hsu and Chen (3) conducted a theoretical analysis of pulsating cavities in an infinite medium. They hypothesized that cavity resonance was an interaction between the flow around the cavity and the compression and expansion of the gas inside the cavity. Therefore, there was no need for a free surface in order to have cavity pulsations.

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* Numbers in parentheses refer to References listed at the end of the paper.

Further experiments were carried out in 1964 by Schiebe and Wetzel (4) in a vertical free jet water tunnel and in a towing tank. It was from a comment in this latter paper that the topic for this thesis arose. It was stated that no experimental work had been performed to verify the theory of Hsu and Chen. The author's survey of the literature in the field revealed that there has been very little experimental work conducted in ventilated cavities.

The purpose of this thesis is twofold.

1. The determination of the feasibility of conducting ventilated cavity experiments in the MIT Propeller Tunnel.

2. An attempt to verify the theory set forth by Hsu and Chen (3).

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* Numbers in parentheses refer to References listed at the end of the paper.
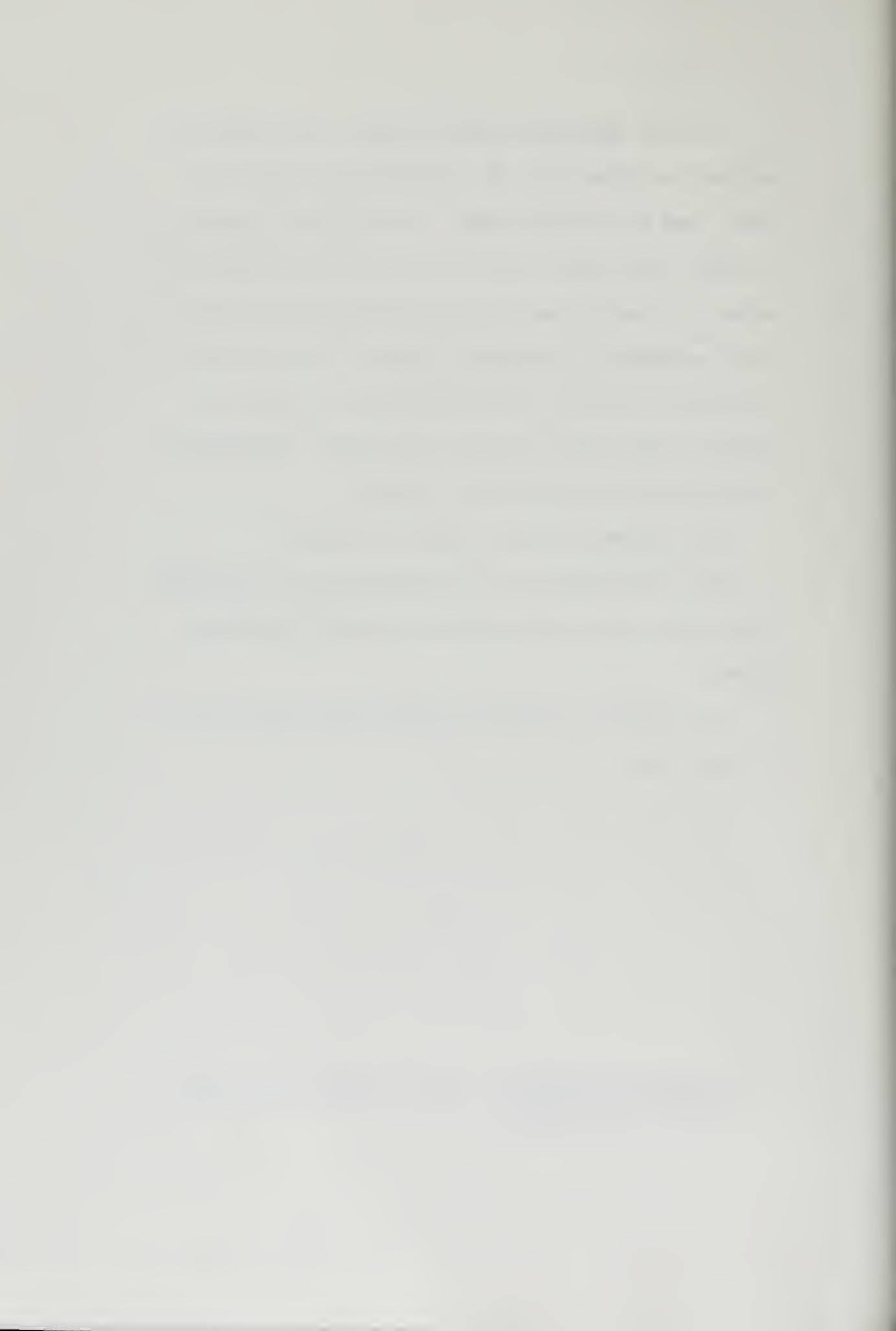
II. PROCEDURE

Description of Equipment

The experiments were conducted in the recently remodeled MIT Propeller Tunnel. The test section is 20 inches by 20 inches by 54 inches and has 2-inch plexiglass windows on all four sides in order to facilitate visual observations.

The tunnel was designed to operate from atmospheric pressure down into the vacuum range. Pneumatic control equipment is used to maintain the tunnel pressure at the desired level. This pressure is the value used as the pressure at infinity in the calculations. Pressure in the cavity is measured by a mercury manometer. The pressure tap is located approximately 4 inches behind the wedge and is flush with the inside face of the plexiglass window. However, during the last series of experiments, this pressure tap was modified so that it extended into the cavity 1/2 inch.

The velocity in the test section is determined by the speed of the impeller which moves the water through the tunnel. The maximum velocity obtainable in the test section is approximately 33 feet per second.
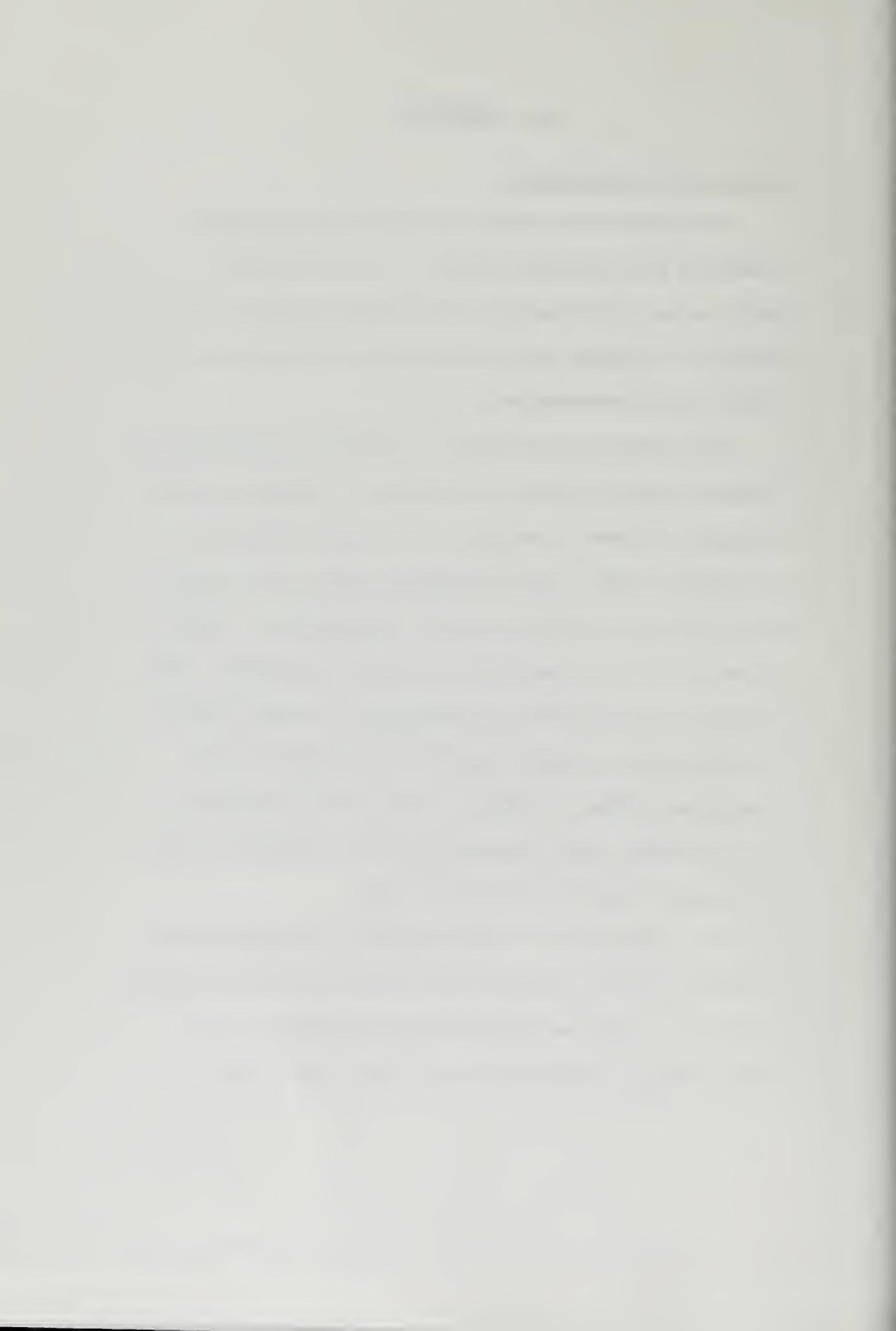
Figure I

Front view of test section.
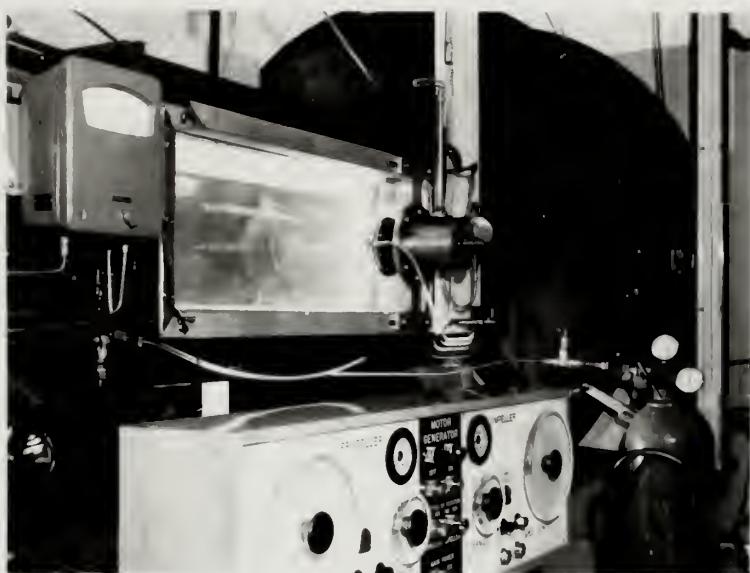
Figure II

Rear view of test section.
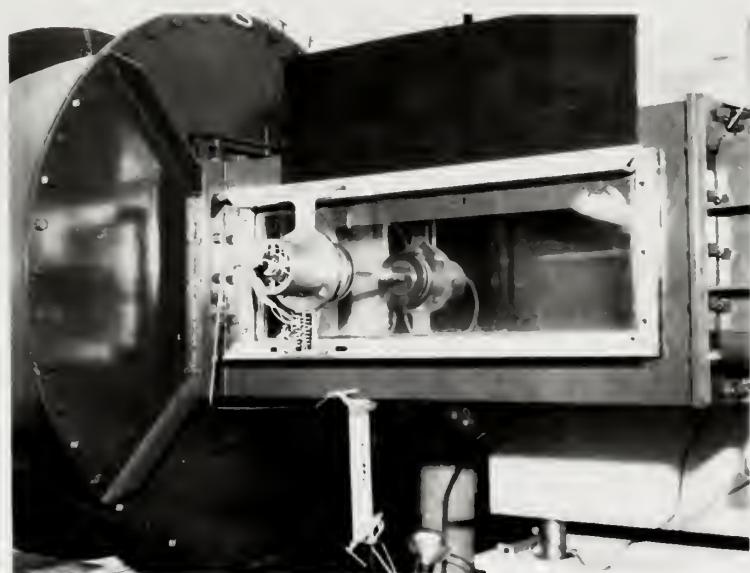
Figure 1 shows the control panel, the pneumatic pressure controller, several manometers, and the air cylinder used to ventilate the cavity. Further description of the tunnel is contained in Reference (5).

The hydrofoil used is a wedge shape with a vertex angle of 8.2 degrees and a chord length of 3.5 inches. In the base of the hydrofoil is a 1/4 inch O.D. copper tube which leads to the exterior of the tunnel through the mounting brackets (see Figure 2). The air supply can be connected at this point or the cavity can be vented to the atmosphere. In the copper tube in the base of the foil are 13 No. 80 holes. The mounting brackets for the wedge are described in detail in Reference (6).

Method

First, a vacuum was drawn on the propeller tunnel. The pressure reached was approximately 100 mm of Hg. absolute. The water velocity in the test section was then increased to a speed above 20 feet per second in order to form a natural cavity behind the wedge. At this point the cavity pressure and the water velocity

were recorded. A high vacuum had to be used because at pressures near atmospheric pressure the hydrofoil was observed to vibrate and bend in the middle. At the higher vacuums there are many more air bubbles present in the tunnel which have a damping affect on the vibration of the foil. Also at the low pressures there exists on the outside of the mounting brackets a force of 14.7 psi whereas on the inside the force is only about 4 psi. This puts additional restraint on the foil. These facts have a tendency to reduce the phenomenon observed at pressures near atmospheric pressure.

Once a natural cavity was established, the valve in the line to the air supply (1500 psi) would be opened slowly. The air entering the cavity was regulated to about 400-500 psi. As the length of the cavity increased, the cavity pressure and corresponding length were recorded. A length of approximately 30 inches was the maximum obtainable in the test section. A length greater than this would have taken the cavity into the diffuser section of the tunnel.

A pitot tube was used to measure the velocity in the test section. This was done without the wedge in the tunnel. Also the tunnel was under a vacuum of 200 mm

of mercury. The pitot tube readings were converted to velocities corresponding to the rpm used to control the flow velocity. This curve is shown in Figure III. There existed a difference in these velocities when compared to the velocities determined at atmospheric pressure.

During one set of runs of the experiment, polaroid photographs were taken some of which will be discussed later. It was difficult to observe anything in some of the pictures due to the high air content of the water with ventilated cavities. An attempt was made to take high-speed movies. A Fastex 16-mm camera was used with a frame speed of 1000 frames per second. Since the area that the author was interested in phot- graphing was approximately 30 inches wide, the camera had to be located away from the tunnel about six feet. Good pictures could not be taken at this distance. The camera could not be moved closer since a wide angle lens was not available.

The Propeller Tunnel may be operated with a free surface by dumping some of the water into a storage tank. This was done during the first phase of the experiment.

Figure III

RPM versus Flow Velocity
(Tunnel pressure = 200
mm of mercury.)

5/7/68   RJK

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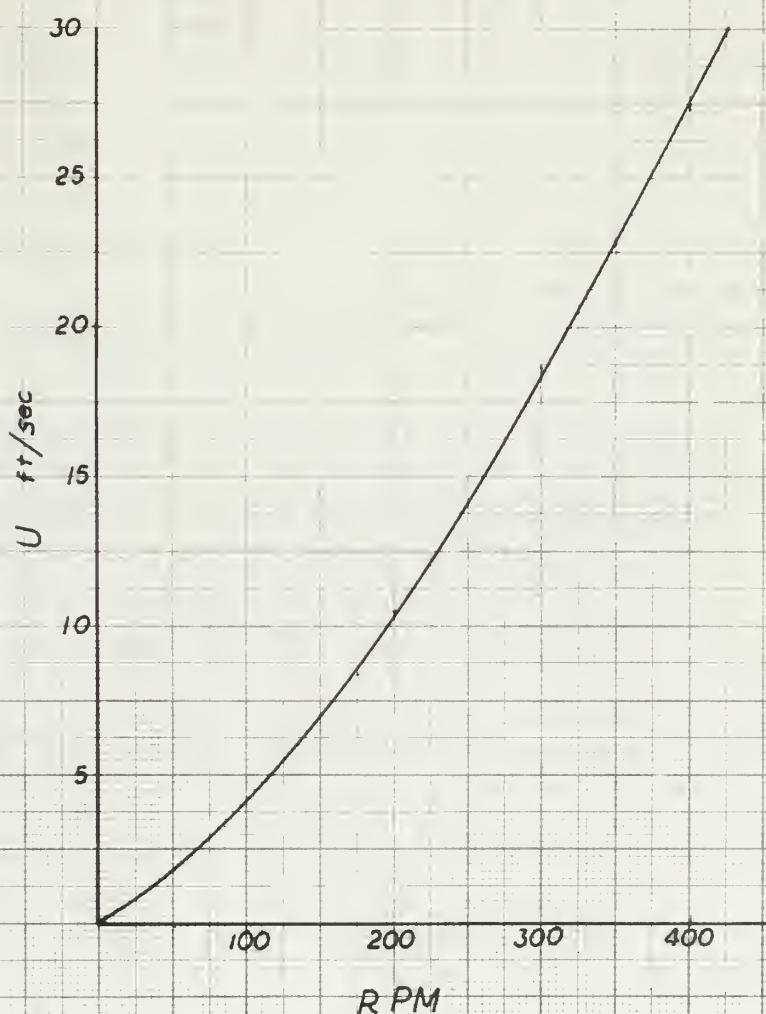
The water level was lowered to about 3 inches below the
top of the test section; the speed was varied; and air
was introduced into the base of the wedge.

III. RESULTS

Pulsating Cavities

The results concerning the pulsation of ventilated cavities are inconclusive. No pulsations were observed in any of the cavities generated. Figure IV shows the cavity resonance conditions for a 15 degree wedge. This figure is adapted from Reference (3). The curves are a plot of cavity pressure over the pressure at infinity versus the flow velocity of the fluid and they represent the first three stages * of pulsation of the cavity at five feet below a free surface. Hsu and Chen (3) assume that the presence of this free surface does not affect the results of their theory, i.e., pulsations in an infinite medium. Cavity resonance is possible when p_c/p_∞ and U_c lie along one of these curves.

Plotted on Figure IV are data interpreted from Silberman and Song (1). One set of points is for a half-span normal plate (1/8 inch plate, 10 inch jet), and the other set is for a half-span hydrofoil (Modified Tulin-Burkhart, 2 1/2 inch chord) at a 12 degree angle of attack in a 10 inch jet. The points for the second and third stages are in agreement with the

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* The stages refer to the number of waves appearing on the cavity.

Figure IV

Cavity Resonance Conditions
from Reference (3)
⊙ 1/8 in.-plate   Ref. (1)
△ Hydrofoil @ 12 degree
   angle of attack
⊟ 8.2 degree wedge   5/1/68 RJK

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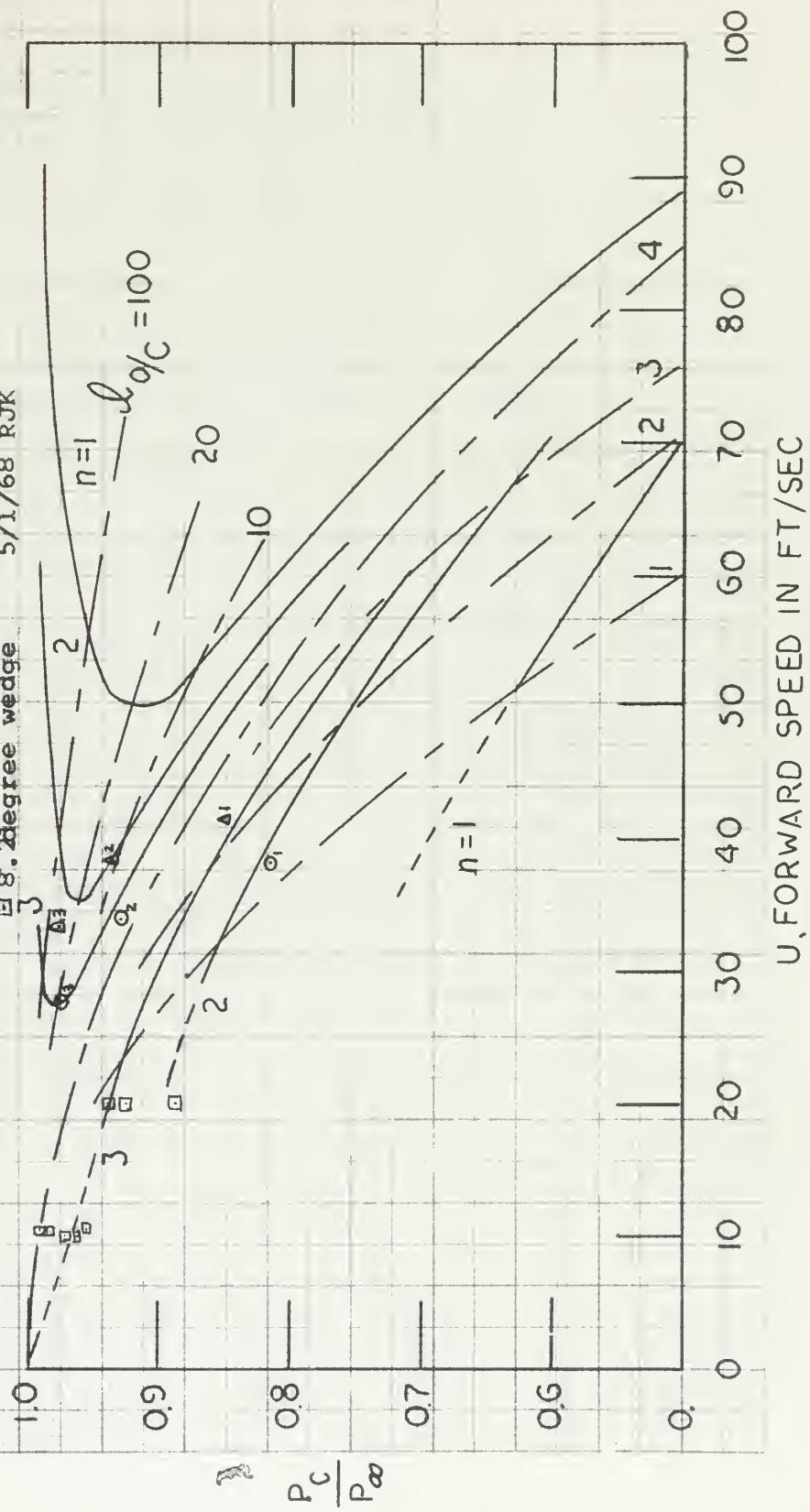
curves of Hsu and Chen. The data for the first stage do
not agree at all.

Points for a 4.1 degree wedge with a 3.5 inch chord
are also plotted. Although some of these points lie on
or near the resonant conditions, no pulsations were
observed by the author.

To determine if pulsations are possible, the condit-
ions for pulsations are taken from Hsu and Chen (3).
These are

$$F_2(k_n/2) = 0 \tag{1}$$

$$M*^2 = \frac{1}{\sigma_0 \ln(l_0/4)} \quad \frac{16}{k^2} \quad F_1(k_n/2) \quad l_0 \neq 4$$

where F_1 and F_2 are equations of Bessel functions with
arguments $k/2$, and these are given in Reference (3).
The following table gives the theoretical values of $k/2$
and $\frac{16}{k^2} F_1(k/2)$ for four stages when $F(k_n/2) = 0$.

Table I
Theoretical results

n		1	2	3	4
$k/2$	$l_0 > 4$	4.2	7.4	10.75	13.7
	$l_0 < 4$	2.75	5.9	9.0	12.1
$\frac{16}{k^2} F_1$	$l_0 > 4$	0.192	0.097	0.055	0.044
	$l_0 < 4$	-1.11	-0.32	-0.16	-0.095

Figure IVa

Equivalent mach number versus
steady part of cavitation number.

——————————— n = 1   n is the
                              number of
— — — — — n = 2   waves on
                              cavity.
— · — · — · — n = 3
                ▢   Data   5/14/68 RJK
                         point

M_*^2

σ_o

13
12
11
10
9
8
7
6
5
4
3
2
1

$l_o = 4.7$
$l_o = 6$
$l_o = 4.7$
$l_o = 6$
$l_o = 5$
$l_o = 8$
$l_o = 6$
$l_o = 5$
$l_o = 8$
$l_o = 6$
$l_o = 8$

.1   .2   .28

13
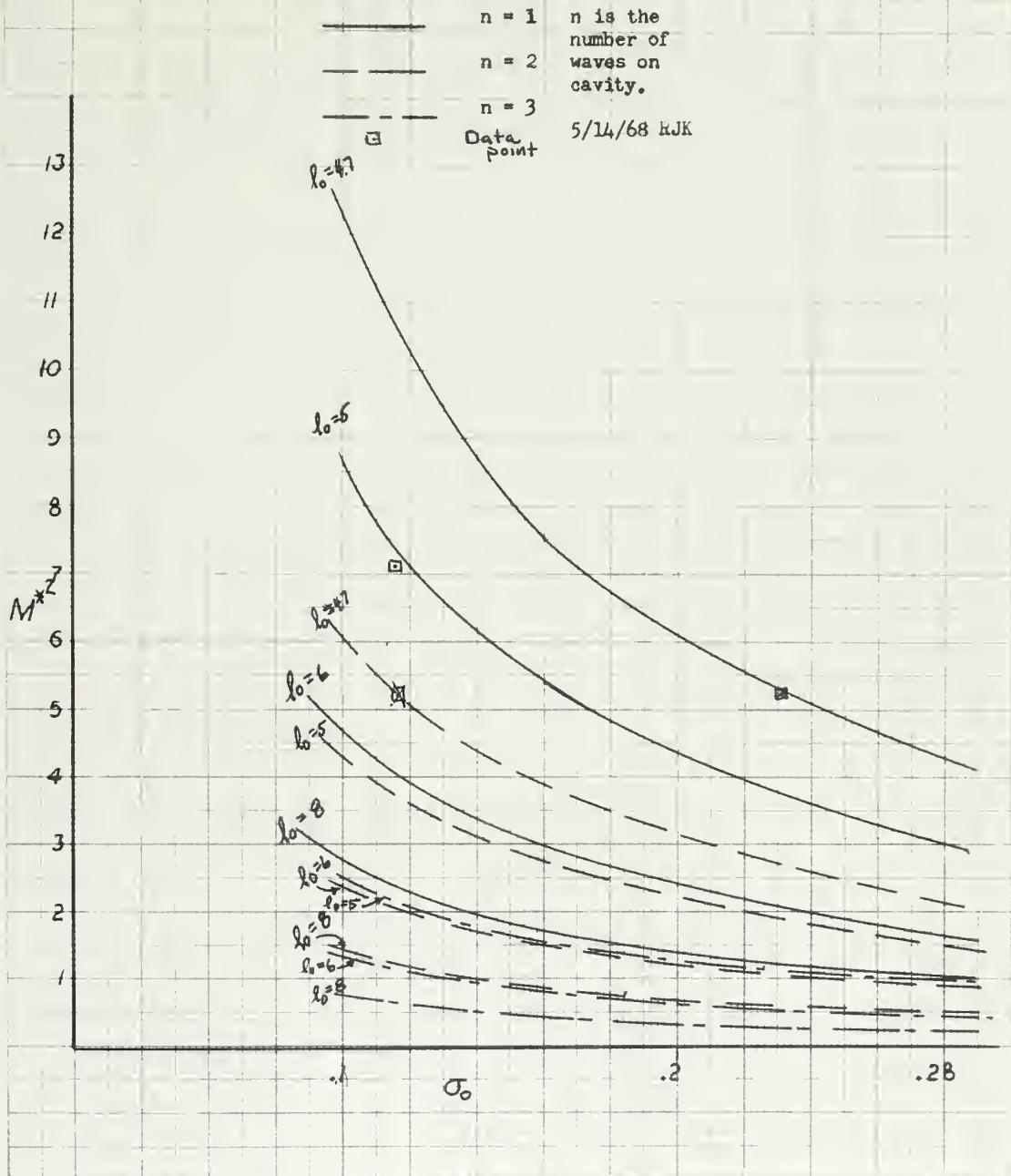
Table II

Data for ventilated cavities.

p_∞ mm of Hg	p_c mm of Hg	U_c fps	l in	l_o
79	53	23.3	18.5	5.15 *
109	89	16.9	9	2.57
84	46	21.4	21.5	6.15
108	81	19.4	14	4
79	37	23.8	22	6.3
81	37	21.7	19	5.4
83	30	22.7	22	6.3
92	59	21.0	16.5	4.7 *
104	73	19.8	6	1.7

* indicates data that was in the pulsating region.

Figure IVa is a plot of equation (1) with various values given for ℓ_0 and n. Since the minimum cavitation number is 0.104, Figure IVa starts near 0.1. This min= imum cavitation number is discussed later.

With the data taken during the experiments, the equivalent Mach number is calculated.

$$M*^2 = \frac{\rho \ U_c^2}{\rho g \ Ag^2} \tag{2}$$

$$Pc = \rho g \ RT \tag{3}$$

$$Ag^2 = RT \tag{4}$$

therefore,

$$M*^2 = \frac{\rho \ U_c^2}{Pc} = \frac{0.696 \ U_c^2}{Pc} \tag{5}$$

with Pc given in mm of mercury and U_c given in feet per second. The cavitation number is also calculated from the given data. From the calculations made on the data, two points were found to lie on the given curves (see Figure IVa). However, no pulsations were observed under these conditions.

While running the tunnel with a free surface, an attempt was made to reproduce some of the results obtained by Silberman and Song (1) and Schiebe and Wetzel (4). Again in the ventilated cavities no pulsations were observed. Other experimenters have had difficulty in reproducing the results of Silberman and Song [10].

Ventilated and Natural Cavities

While no definite results were collected concerning the pulsation of ventilated cavities, some data were gathered on the natural and ventilated cavities that were produced. These data are plotted in Figure V along with some theoretical curves. The generally accepted correlation parameter is the cavitation number, σ, where

$$\sigma = \frac{P_O - P_C}{\frac{1}{2} \rho U_\infty^2} \tag{6}$$

Figure V is a plot of sigma versus beta (B).

Since the experiment was conducted with solid walls, a correction factor was applied to the velocity to determine the cavitation number. This correction was also used since the velocity measurements taken for the test section were done so without a hydrofoil mounted. Following the manner of Birkhoff (7), the simplified form of Bernoulli's equation

$$\frac{1}{2} \rho U_\infty^2 + P_\infty = \frac{1}{2} \rho U_C^2 + P_C \tag{7}$$

is used. When this equation is solved for $P_\infty - P_C$ and is substituted into equation (6), the result is

$$\frac{U_C}{U_\infty} = \sqrt{\sigma + 1} \tag{8}$$

Figure V

Cavitation Number versus Chord Length
to Cavity Length Ratio
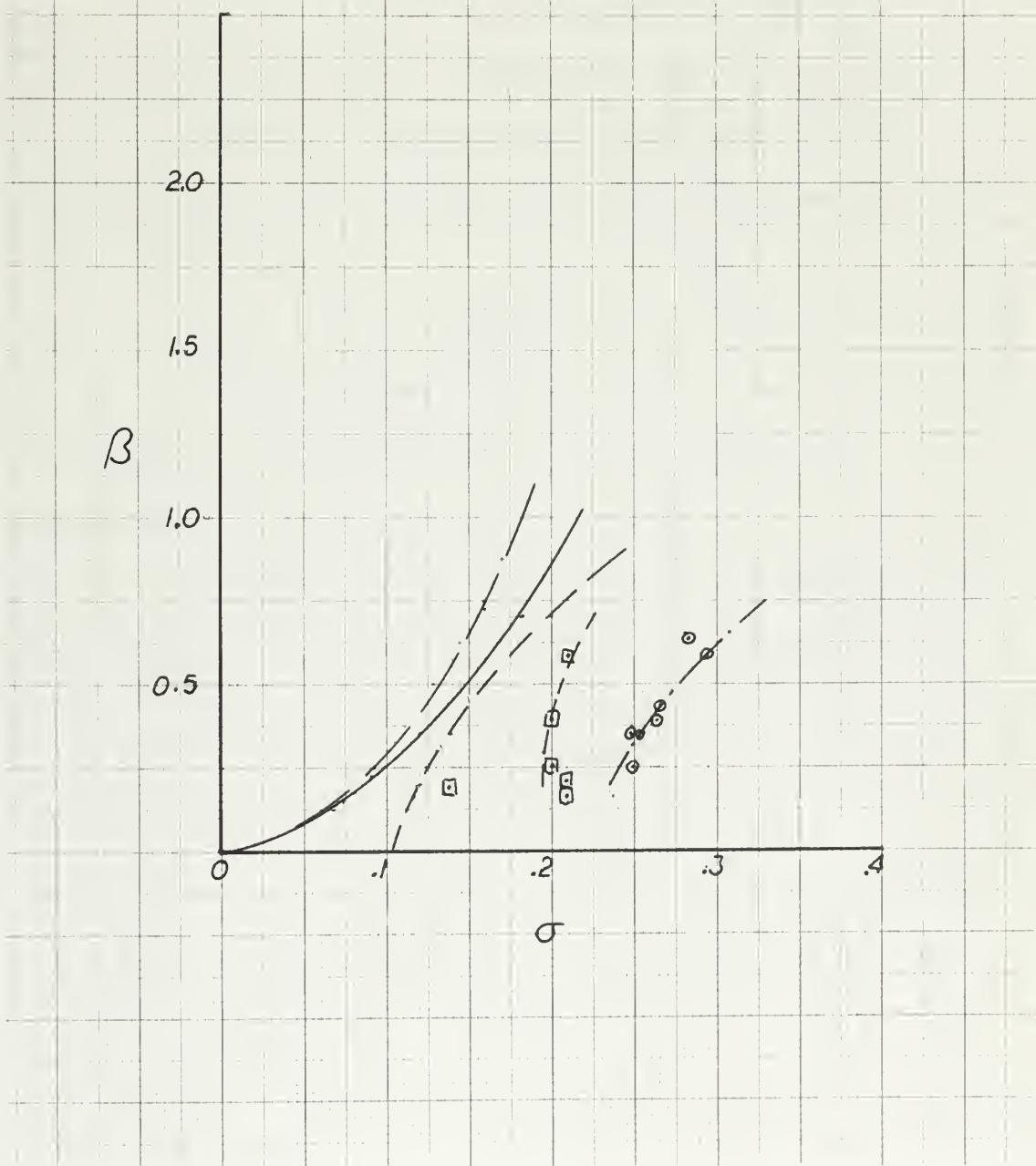
Upon linearizing this equation we obtain

$$U_c = U_\infty \left[1 + \frac{1}{2}\sigma \right] \tag{9}$$

The value of sigma used in equation (9) is the one
calculated from the theoretical results of Cohen and
Gilbert. This is discussed below. The calculated U_c
is then used to determine the experimental cavitation
number. The results are approximately the same as those
that would have been derived if the reduction in cross
sectional area of the flow due to cavity width had been
used to determine U_c.

One of the curves (Figure V) is the asymptotic re-
sults for an inclined wedge as developed by Leehey (8).
This result is valid for $\sigma \ll 1 \; (\ell_0 \gg 1)$ and is as
follows:

$$\sigma = \frac{8}{\pi}\gamma \ell_0^{-\frac{1}{2}} \tag{10}$$

This theory is for an infinite medium.

The other two theoretical curves plotted were det-
ermined from the results of Cohen and Gilbert (9) dealing
with wall effects on cavity flow. The reduced equation
for an infinite stream is plotted. The equation for this
curve is

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$$\frac{\sigma}{1+\frac{\sigma}{2}} = \frac{4\gamma}{\pi}\left\{\sqrt{\beta(1+\beta)} + \ln\left[\sqrt{\beta} + \sqrt{1+\beta}\right]\right\} \quad (11)$$

At high cavity lengths (low B) equations (10) and (11) agree quite well. But the curves begin to separate as the length decreases.

The equation that takes into account the solid walls is

$$\frac{\sigma}{1+\frac{\sigma}{2}} = \frac{2\gamma}{\pi}\left\{\coth\frac{\pi a}{2\beta}\ \tanh^{-1}\left[\sqrt{\frac{\sinh\pi a\ \sinh\frac{\pi a(1+\beta)}{\beta}}{\cosh\frac{\pi a(1+2\beta)}{2\beta}}}\right]\right.$$
$$\left. + \tanh^{-1}\left[\sqrt{\frac{\sinh\pi a\ \sinh\frac{\pi a(1+\beta)}{\beta}}{\sinh\frac{\pi a(1+2\beta)}{2\beta}}}\right]\right\} \quad (12)$$

This equation is plotted with a half-wedge angle of 4.1 degrees, a channel breadth of 20 inches, and a chord length of 3.5 inches.

The limiting cavitation number under the test conditions is calculated from Cohen (9):

$$\frac{\sigma_\infty}{1+\frac{\sigma_\infty}{2}} = \frac{4\gamma}{\pi}\cosh^{-1}\left[e^{\pi a}\right] \quad (13)$$

where σ_∞ = cavitation number at B = 0. The value of this limit is 0.104.

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The experimental results are plotted for natural cavities and for ventilated cavities. The general shape of the curves agrees quite well with the theoretical curve with the presence of walls taken into account. However, there is a discrepancy of about .12 in the range of cavitation numbers covered.

Study of Ventilated Cavities

It is possible to conduct experiments on ventilated cavities in the MIT Propeller Tunnel, but there are some limitations. One is the maximum velocity obtainable without doing possible damage to the tunnel. The author was able to reach only a velocity of approximately 25 feet per second. Even at this speed the tunnel near the test section began to vibrate causing the pneumatic equipment mounted on the tunnel to vibrate. Also at this speed there existed considerable noise in the diffuser section and in the turning vanes when air was introduced into the cavity.

The other limitation is the extent to which visual observations are possible. As mentioned earlier, polaroid pictures were taken, but they were of such a nature that one had to know what to look for in order to see the re-entrant jet and the trailing edge of the cavity.

The pictures taken of the natural cavities clearly show
the top side of the test section (all pictures of re-
entrant jets were taken from the bottom) so that photo-
graphing through the 2 inches of plexiglass and the
water is not a problem.

Figure VI shows a drawing of the general shape of
a natural cavity. When the cavity is first formed, the
re-entrant jet impinges on the base of the wedge (over
the entire span). The jet has nearly a rectangular
shape when viewed from the top or bottom. As the speed
is increased or as the pressure is decreased, the cavity
length increases. The re-entrant jet retains its approx-
imately rectangular shape as the cavity grows and it
impinges on the center portion of the wedge. Eventually
the jet no longer strikes the wedge but is as shown in
Figure VI.

The problem of observing ventilated cavities is much
more difficult than with natural cavities. At about 19
feet per second the re-entrant jet was verily well defined.
Figure VII shows a drawing of the general nature of a
ventilated cavity. It differs from the natural cavity
in that it does not have the rectangular shape across
the trailing edge of the cavity. This is due to the flow

Figure VI

Drawing of the general nature of the
re-entrant jet of a natural cavity.
(Not to scale.)
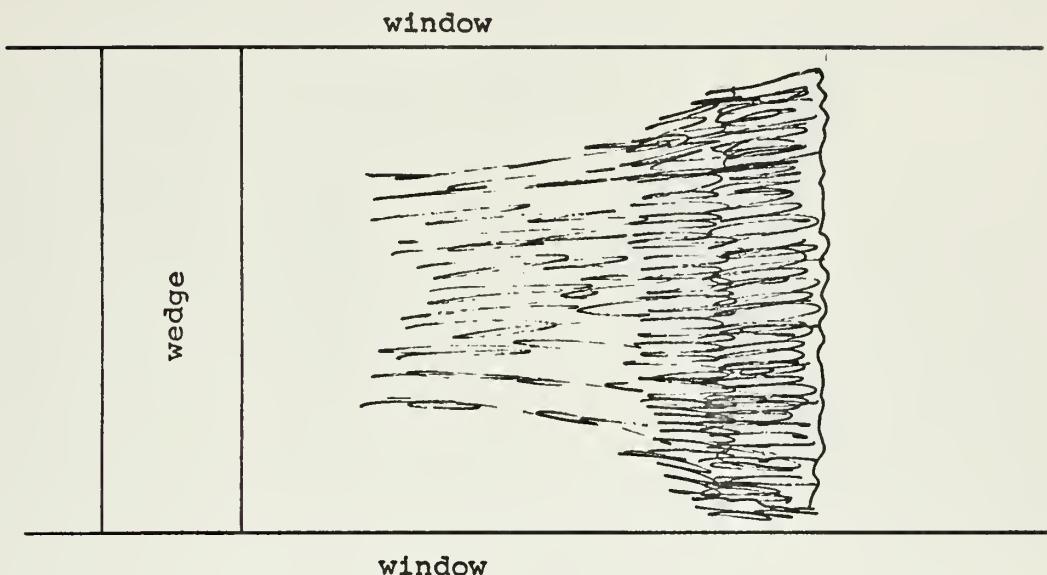
Figure VII

Drawing of the general nature of the
re-entrant jet of a ventilated cavity.
(Not to scale.)
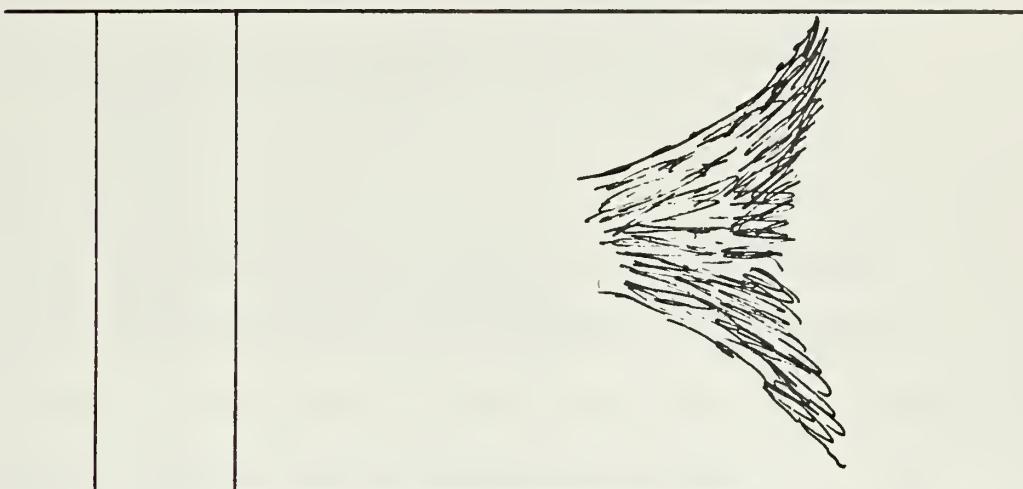
of air in the cavity that is being introduced through the base of the wedge. As the air injection increased the cavity grew until it reached a point where the center part of the re-entrant jet was completely disrupted. In this case the inflow of air was much greater than the outflow through entrainment in the re-entrant jet.

During one experimental run, the air inlet to the base of the wedge was left open to the atmosphere. The velocity of the water was about 11 feet per second. Under these conditions the parameter that was varied was p_∞. As the tunnel pressure was reduced the cavity length increased and p_c remained less than p_∞. The length of the cavity at this point was about 14 inches. Then as the pressure was decreased beyond 427, p_c was less than p_∞ but there existed no substantial increase in cavity length beyond 14 inches. At the point where $p_c > p_\infty$, the cavitation number is negative and the theory for cavity flows does not apply.

The water tunnel may be operated with a free surface, but at high speeds the water level builds up in the upstream direction causing the flow through the test section to be at an angle from upstream to downstream. Through

Figure VIII

Ventilated cavity with free surface.

Figure IX

Bottom view of Figure VIII.

trial and error the wedge position was adjusted so that
the effective angle of attack with respect to the flow
was zero. Figures VIII and IX show a side view and a
bottom view of the wedge with air being introduced.
With a vacuum being drawn on the tunnel, it is observed
that the air rises immediately to the free surface in
the downstream direction. Only short cavities were pro-
duced in this manner. Large bubbles are observed in these
two pictures even though the size of the holes in the
base of the wedge are only No. 80. This is due to the
pressure in the tunnel being lower than the air entering
causing the bubbles to expand.

IV. DISCUSSION OF RESULTS

The data of Silberman and Song (1) plotted in Figure IV agrees very well with the theory of Hsu and Chen even though the shapes of the bodies used are different and in their experiments a free surface was present. This difference in shapes may attribute to the lack of agreement for the first stage.

The data plotted by the author in Figure IV lay in the low speed range (10-20 fps) of the curves. The fact that high speeds were not obtainable in the present test section contributed to the lack of cavity pulsations. A prospect for future experimentation is the use of a collapsable nozzle to give a greater area reduction that may be inserted into the present test section. Thus higher velocities will be obtainable.

The data points plotted in Figure V tend to verify equation (12) which takes into account the effect of solid boundaries. Also as expected the ventilated cavities are longer than the corresponding natural cavities. There does appear to be, however, a discrepancy in the cavitation numbers for the theory and the experiment. The author attributes this mainly to method in which pressures were measured. The measured pressures inside

the natural cavities were generally larger than the vapor

pressure of water. The discrepancy is shown in Figure ~~VIII~~ X.

Initially cavity pressures were measured with the

pressure tap flush with the test section wall in the

cavity region. The device used was a crude mercury mano-

meter made by the author. The data taken using this press-

ure tap were widely dispersed. The tap was modified so

that it extended into the cavity about 1/2 inch. The

data taken then were more uniform.

The pressure used as p_∞ was the static pressure

measured at the forward end of the test section. This

was the pressure used to control the pneumatic equipment

which regulated the vacuum in the tunnel. At high speeds

this pressure was observed to vary greatly. The probable

cause of this is the boundary layer effect at the entrance

to the test section. Another source of error was in the

difficulty in maintaining the lines leading to the mano-

meters filled with water when a low vacuum was being

drawn on the tunnel.

Figure X

Comparsion between cavitation number
based on vapor pressure and cavitation
number based on measured cavity pressure.
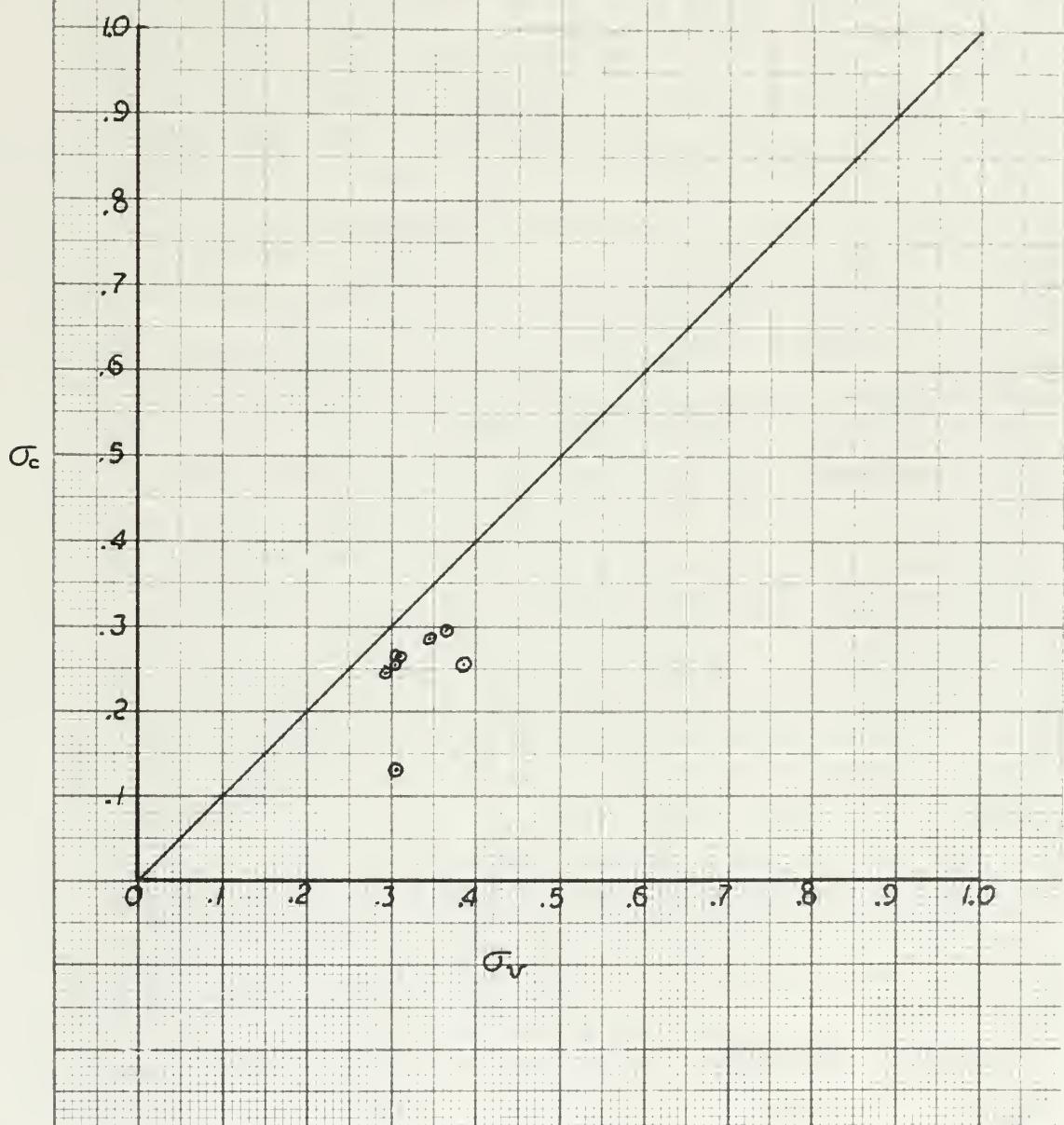
V. CONCLUSIONS AND RECOMMENDATIONS

1. It was not possible to produce pulsating cavities in the MIT Propeller Tunnel. Therefore, no conclusions may be drawn in regards to the theory developed by Hsu and Chen (3).

2. The theory concerning wall effects appears to be quite good. The shape of the experimental results verifies this although there is a discrepancy in the cavitation numbers. This is due to the unsophisticated method of measuring the pressures.

3. The study of cavity flows can be accomplished in the MIT Propeller Tunnel; however, visual observations are limited when ventilation is used since the water fills up with air bubbles, and these are circulated through the tunnel.

4. Further investigations of pulsating cavities might be conducted in the tunnel. There is the possibility of using different shapes and wedges with larger half-angles.

5. A nozzle that can fit into the existing test section may be designed to give a smaller exit area. Higher speeds would then be possible.

6. Re-entrant jets may be studied to compare with theory.

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